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# Wideband Piezomagnetoelastic Vibration Energy Harvesting

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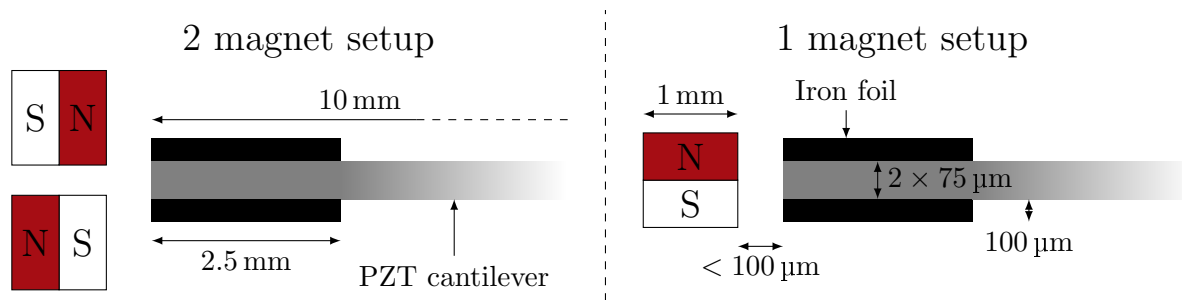
**Abstract.** This work presents a small-scale wideband piezomagnetoelastic vibration energy harvester (VEH) aimed for operation at frequencies of a few hundred Hz. The VEH consists of a tape-casted PZT cantilever with thin sheets of iron foil attached on each side of the free tip. The wideband operation is achieved by placing the cantilever in a magnetic field induced by either one or two magnets located oppositely of the cantilever. The attraction force created by the magnetic field and iron foils introduces a mechanical force in opposite direction of the cantilevers restoring force causing a spring softening effect. In linear operation (without magnets) the harvester generates a RMS power of  $141 \mu\text{W}/g^2$  at 588 Hz with a relative bandwidth of 3.8% over a  $100 \text{ k}\Omega$  load resistor. When operated with one magnet ideally positioned opposite the cantilever, a RMS power of  $265 \mu\text{W}/g^2$  is generated at 270 Hz with a relative bandwidth of 25%.

## 1. Introduction

Small-scale vibration energy harvesters (VEH) have attracted significant attention as power-source for autonomous wireless systems. A development highly stimulated by the significant advances in low power electronics and especially sensor units such as gyroscopes and accelerometers. One of the main challenges for VEHs is that a high quality factor provides high peak power but low frequency bandwidth and vice versa. High output power is essential, but low bandwidth is an issue if the source vibration frequency is drifting over time. Another challenge for small-scale VEHs is to keep the resonant frequency sufficiently low. This is usually achieved by vibrating structures with a very high aspect ratio between length and thickness which often results in an inherently fragile harvester. One approach to address these two key challenges is to introduce an external force in addition to the vibrating structure's internal spring restoring force. The result is a non-linear VEH that depending on the external force can be either multi-stable or monostable. A multi-stable harvester will have two or more stable points separated by a potential energy barrier. The harvester can therefore achieve high deflection at low frequencies due to switching between the stable points [1]. A monostable harvester will depending on the external force experience an either increasing or decreasing effective spring constant. The latter is desirable for energy harvesting as the effective resonant frequency is decreased while the harvester deflection is increased. High generated power can therefore be obtained with a high relative bandwidth.

The external force can be induced using both active or passive techniques. Since the objective of a VEH is to deliver power, passive techniques such as permanent magnets are naturally of preference. A setup with magnets usually consist of one or more external magnets and either





**Figure 1.** Sketch of the two magnetic setup investigated.

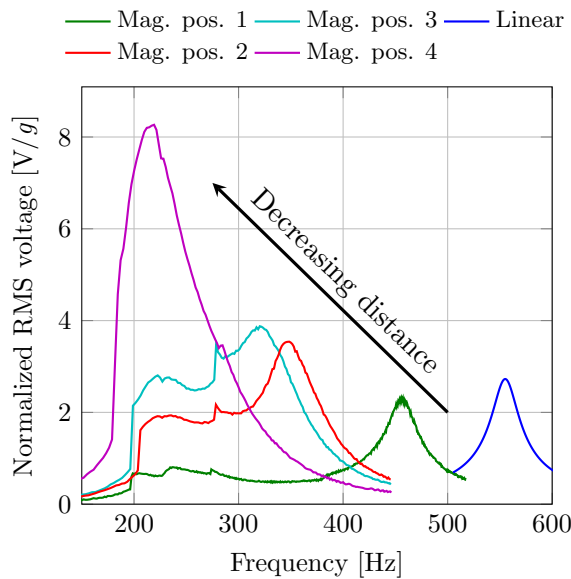
a permanent magnet or a ferromagnetic material on the harvester. Repelling forces can be achieved with a permanent magnet on the harvester but the realization of this is especially difficult on a small-scale. The majority of magnetic enhanced VEHs presented in literature are therefore proof-of-concept systems on a macroscopic scale [2–4] while only very few small-scale devices are reported [5]. The VEH presented in this work is comprised of a PZT based cantilever with dimensions suitable for a realistic packaging and implementation into a wireless sensor system. The magnetic setup utilizes ferromagnetic foils on the cantilever permanent magnets positioned oppositely the cantilever. Two different magnet setups with either one or two magnets are investigated, see figure 1. Two magnets creates the strongest attraction force but in an packaging assembly one magnet might be easier to implement.

## 2. Experimental setup

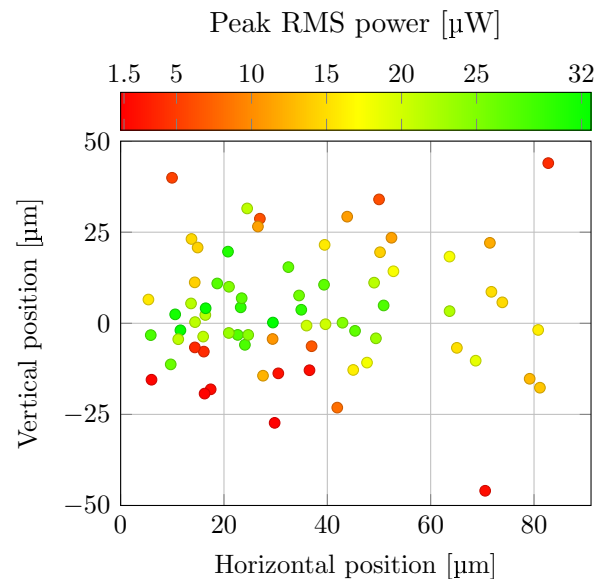
The VEH setup is sketched in figure 1 and is comprised of a 6 mm wide and 10 mm long cantilever diced from a tape-casted two-layered sheet of PZT. Each of the two PZT layers has a thickness of  $75\ \mu\text{m}$  with two outer and one middle conducting layers covering the full area. The cantilever is anchored to a PCB through soldering. The two PZT layers are poled in opposite directions, hence only electrical contacts to the two outer conducting layers are required. A  $100\ \mu\text{m}$  thick iron foil of 5.5 mm in width and 2.5 mm in length is attached on each side of the cantilevers free tip using glue. The magnets are attached in a fixture which is mounted on a XYZ 500 micropositioner stage from Quater Research and Development. The magnets are NdFeB with a size of  $1\ \text{mm} \times 1\ \text{mm} \times 5.5\ \text{mm}$  and a magnetization of  $750\ \text{A m}^{-1}$  from Webcraft GmbH. The PCB with cantilever and the stage with magnets are mounted on an aluminum fixture which then is attached to a TIRA TV51110 shaker system. The shaker is driven by a Agilent 33250A function generator and the input acceleration measured using a B&K Piezoelectric Accelerometer 8305 in connection with a B&K Type 2692-A-0I2 Charge Conditioner. The position of the magnet setup are measured using two laser displacement sensors from Micro-Epsilon. An optoNCDT 2300-10 for the vertical position and an optoNCDT 1401-5 for the horizontal position.

## 3. Measurements

The shaker is excited with a continuous sinusoidal frequency sweep from low to high value with a scan rate of  $1\ \text{Hz s}^{-1}$ . The harvester is connected to a 1040 resistance box from Time Electronics and the generated voltage is measured using a NI USB-6210 DAQ. The RMS voltage ( $V_{\text{RMS}}$ ) frequency response is then extracted using a synchronization signal from the function generator, and the generated RMS power is calculated as  $P = V_{\text{RMS}}^2/R$  where the load  $R$  is  $100\ \text{k}\Omega$  for all measurements. The measured acceleration is stated in gravitational unit  $g = 9.82\ \text{m s}^{-2}$ .



**Figure 2.** Harvester voltage response with no magnets (linear) and with the two magnet setup at four different distances.



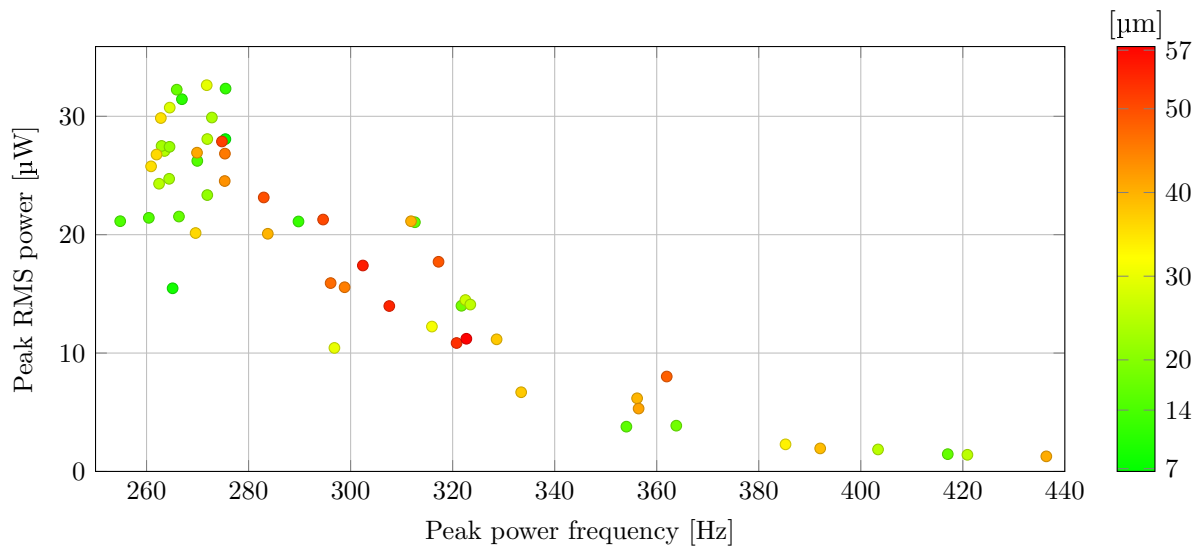
**Figure 3.** Peak RMS power as function of vertical and horizontal position of the two magnets relative to the cantilever tip.

### 3.1. Position study with 2 magnets

The induced magnetic force is naturally highly dependent on the strength of the magnetic field and hence the distance from cantilever tip with iron foils to the magnets. This distance dependency is examined in figures 2-3 using an excitation acceleration of  $0.25g$ . Figure 2 shows the voltage response for the linear case with no magnets present and for four different magnet positions where the distance is gradually decreased. As the magnets are moved closer to the cantilever the magnetic field around the iron foil increases in strength. The induced magnetic force decreases the linear spring force, the results is both a significant decrease in peak voltage frequency and an increase in generated voltage as the cantilever deflection increases due to the lower spring stiffness.

A comprehensive study of the magnet position dependency is seen in figure 3 as a scatter-plot with vertical and horizontal positions of the magnets relative to the cantilever tip. The beneficial non-linear effects of the two magnets vanished rapidly at horizontal distances of more than  $100\text{ }\mu\text{m}$  from the cantilever tip. Ideally the magnets should be positioned less than  $50\text{ }\mu\text{m}$  from the cantilever tip. The vertical axis is even more sensitive as only a position within a range of approx.  $30\text{ }\mu\text{m}$  is of interest. The asymmetry around the cantilever axis in figure 3 is caused by a slight tilt between magnets and cantilever which is not possible to adjust with the XYZ 500 micropositioner stage. Despite using two permanent magnets with a high magnetization, a high precision of the magnet positions are required relative to the millimeter scale of the cantilever and magnet dimensions.

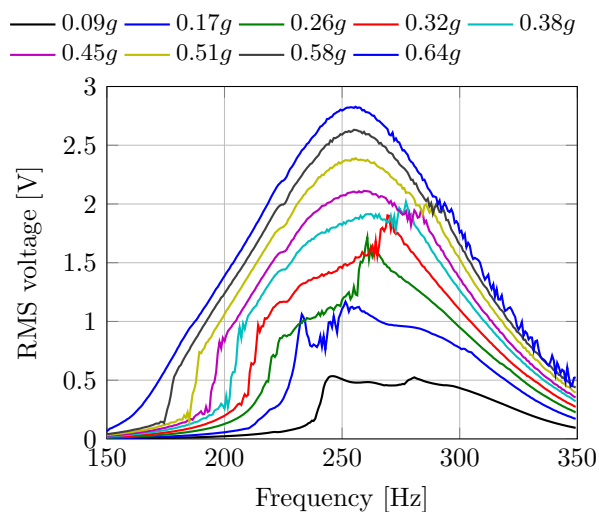
The non-linear force from the magnets not only increases the generated power, it also decreases the peak power frequency as seen in figure 2. This is naturally equally desirable as most ambient sources of vibrations are at a maximum of a few hundred hertz. Figure 4 shows the peak power measurements in figure 3 as function of peak power frequency with the magnitude of the scatter-plot being the absolute distance between magnets and cantilever tip. The correlation between lower peak power frequencies resulting in higher generated power is evident as is the required precision of the magnets position.



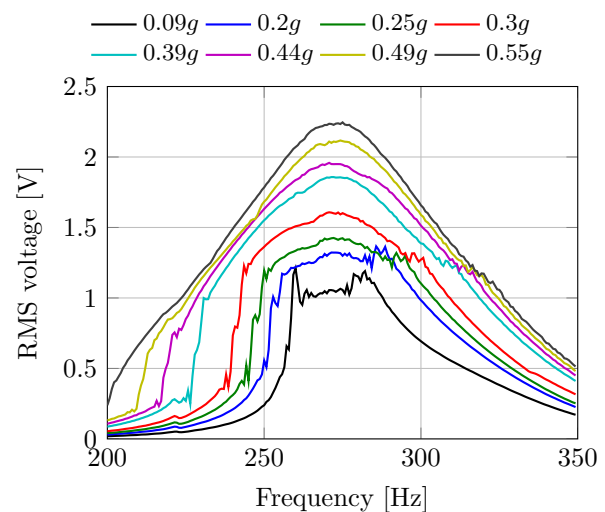
**Figure 4.** Peak RMS power as function of peak power frequency. Scatter magnitude is the absolute distance between magnets and cantilever tip.

### 3.2. Acceleration study for 1 and 2 magnet setup

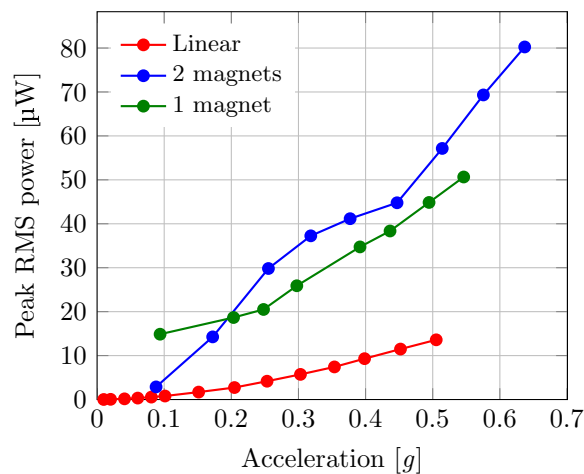
The measurements in figures 2-4 are all performed with an input acceleration of  $0.25g$ . Figures 5-6 show the voltage response for different input accelerations with the 2 magnet and 1 magnet setup at a fixed optimal position. The ripples on the voltage response in the frequency range from 250 Hz to 350 Hz are caused by vibrations of the micro-stage. These stage vibrations results in asymmetric voltage responses at low accelerations for both magnet setups. A consequence of this voltage asymmetry is that the evaluation of peak voltage frequency and bandwidth are resulting in a high variation.



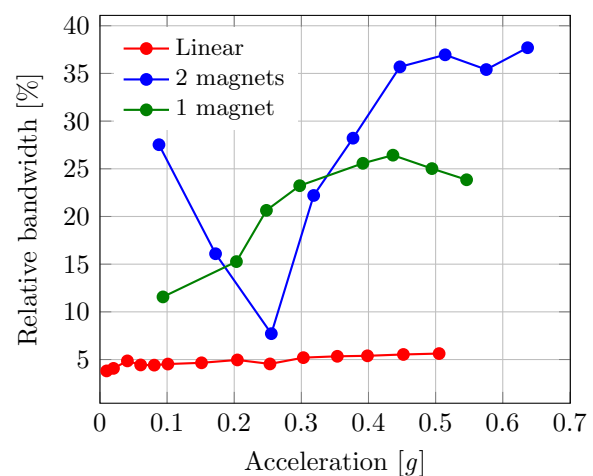
**Figure 5.** Voltage response with 2 magnets for different input accelerations.



**Figure 6.** Voltage response with 1 magnet for different input accelerations.



**Figure 7.** Peak RMS power as function of acceleration for the two magnet setups and without magnets.



**Figure 8.** Relative bandwidth as function of acceleration for the two magnet setups and without magnets.

The summarized peak RMS power for both magnet setups are plotted in figure 7 together with the results for the harvester under linear operation without magnets. Using either of the two magnetic setups results in a significant increase in generated power compared to the linear harvester. While two magnets results in higher power than one magnet, the additional packaging challenge of precise positioning of two magnets should be taking into consideration. The relative bandwidth for the measurements in figure 7 are plotted in figure 8. Both magnet setup results in a considerable increase of the relative bandwidth. The fluctuations for the 2 magnet setup is caused by the asymmetric voltage response seen in figure 5. For the 1 magnet setup the magnetic field is perpendicular to the iron foil, the vertical vibrations of the stage is therefore considerable less influencing.

#### 4. Conclusion

Wideband piezoelectric vibration energy harvesting has been demonstrated on a 6 mm wide and 10 mm long cantilever with external magnetic forces. The internal spring restoring force of the cantilever is compensated by attraction forces between thin iron foils at the free cantilever tip and magnets placed oppositely. The result is a decrease in effective resonant frequency, increase in generated power and a considerable enhancement of the relative harvesting bandwidth. In linear operation (without magnets) the harvester generates a RMS power of  $141 \mu\text{W}/g^2$  at 588 Hz with a relative bandwidth of 3.8% over a 100 kΩ load resistor. When operated with two magnets ideally positioned opposite the cantilever, a RMS power of  $502 \mu\text{W}/g^2$  is generated at 217 Hz with a relative bandwidth of 25%. With only one magnet, a RMS power of  $265 \mu\text{W}/g^2$  is generated at 270 Hz with a similar relative bandwidth of 25%.

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